SeaSoar and Doppler Sonar Spatial Survey of Internal Tide Generation, Surface Boundary Layer Dynamics, and Mixing

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LONG-TERM GOALS

This research is a component of the Assessing the Effectiveness of Submesoscale Ocean Parameterizations (AESOP) Departmental Research Initiative. Its overall goal is to assess parameterizations in regional models of processes with lateral scales of 100 m-10 km. Our SeaSoar survey will contribute to an improved understanding of two distinct fields, surface boundary layer dynamics and internal tides.

OBJECTIVES

Our objectives cover three themes: surface boundary layer dynamics, the decay of submesoscale activity away from the coast, and internal tide generation and dissipation. A coordinated dataset of sufficient resolution and extent will help improve parameterizations for submesoscale processes. Modelling work shows submesoscale fronts and eddies decay away from the coastal upwelling zone, but further observations are needed. Internal tide-driven mixing may substantially increase mixing in the water column away from boundaries and presently tides are not included in most regional models.

- Surface boundary layer dynamics
  - How does submesoscale horizontal variability affect the surface mixed layer and the transition layer below it?
  - Where does vertical mixing take place at a front?

- Submesoscale decay away from the coast
  - What is the observed statistical description (e.g., temperature gradient horizontal wavenumber spectra, vorticity probability distribution functions)?
  - How does it compare to a high-resolution regional model?

- Internal tide generation and dissipation
    - Where is the internal tide generated in the Monterey Bay area?
    - How and where is it dissipated?
    - How well do parameterizations describe internal tide-driven mixing?

APPROACH

Observations. During the AESOP field program near Monterey Bay, our cruise from 29 July-28 August 2006 was divided into 3 segments: a front survey from 30 July-6 August, an offshore line to examine submesoscale decay away from the coast from 6-10 August, and an internal tide survey from 10-25 August. SeaSoar was towed behind a ship at 4 m s^{-1} and made sawtooth profiles to depths of 400 m. We obtained observations of 1) hydrography from 0-400 m at 8-m vertical and ~3-km horizontal resolution from a SeaSoar equipped with a CTD, fluorometer, oxygen sensor, and transmissometer; 2) microstructure from a Transmitting Microstructure System (TMS) mounted below the SeaSoar (Figure 2); and 3) currents to depths of 100, 400, and 600 m at vertical resolutions of 4, 8, and 16 m using vessel-mounted acoustic Doppler current profilers (ADCP). Our measurements are of similar horizontal resolution to regional models and can be used to validate numerical model output and their parameterization schemes. Conductivity microstructure can be used to determine the Cox number, from which the diffusivity and the dissipation of temperature gradient variance can be calculated. The advantage of using the SeaSoar to obtain microstructure measurements is that a large area can be surveyed rapidly and repeatedly.
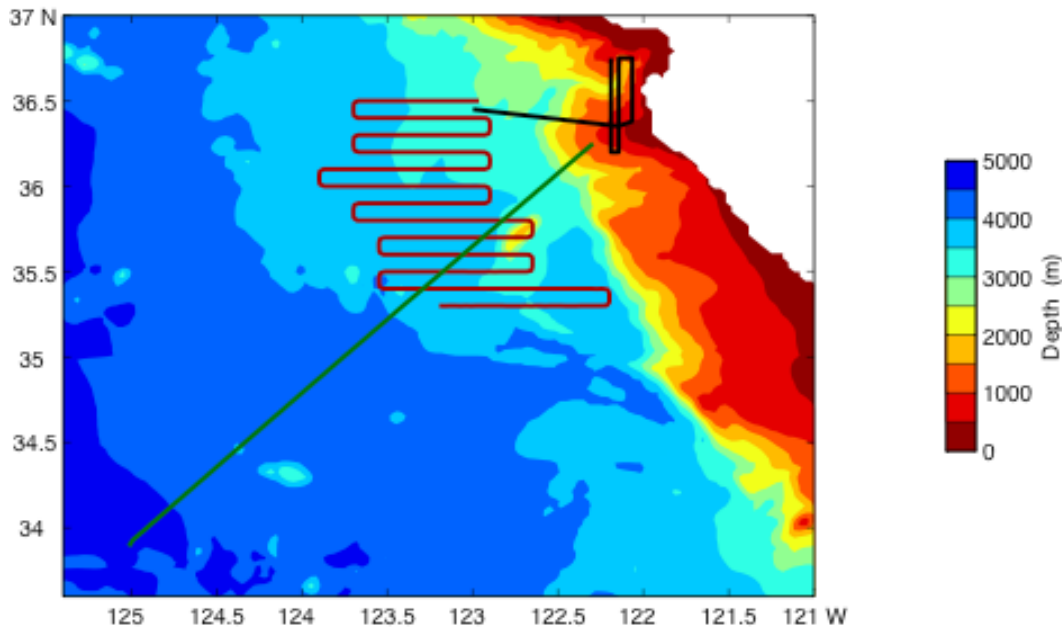

Figure 1. The cruise consisted of 3 segments near Monterey Bay: a front survey (red), an offshore line (green), and an internal tide survey (black). R/P FLIP was moored between our east and central internal tide lines. The front was located ~100 km offshore and the survey had thirteen cross-front legs, which are ~70 km long and separated by 11 km. The offshore line extended ~400 km offshore from Point Sur and was perpendicular to the coast. The internal tide survey repeated three lines near Sur Platform about twenty times and an offshore line four times.
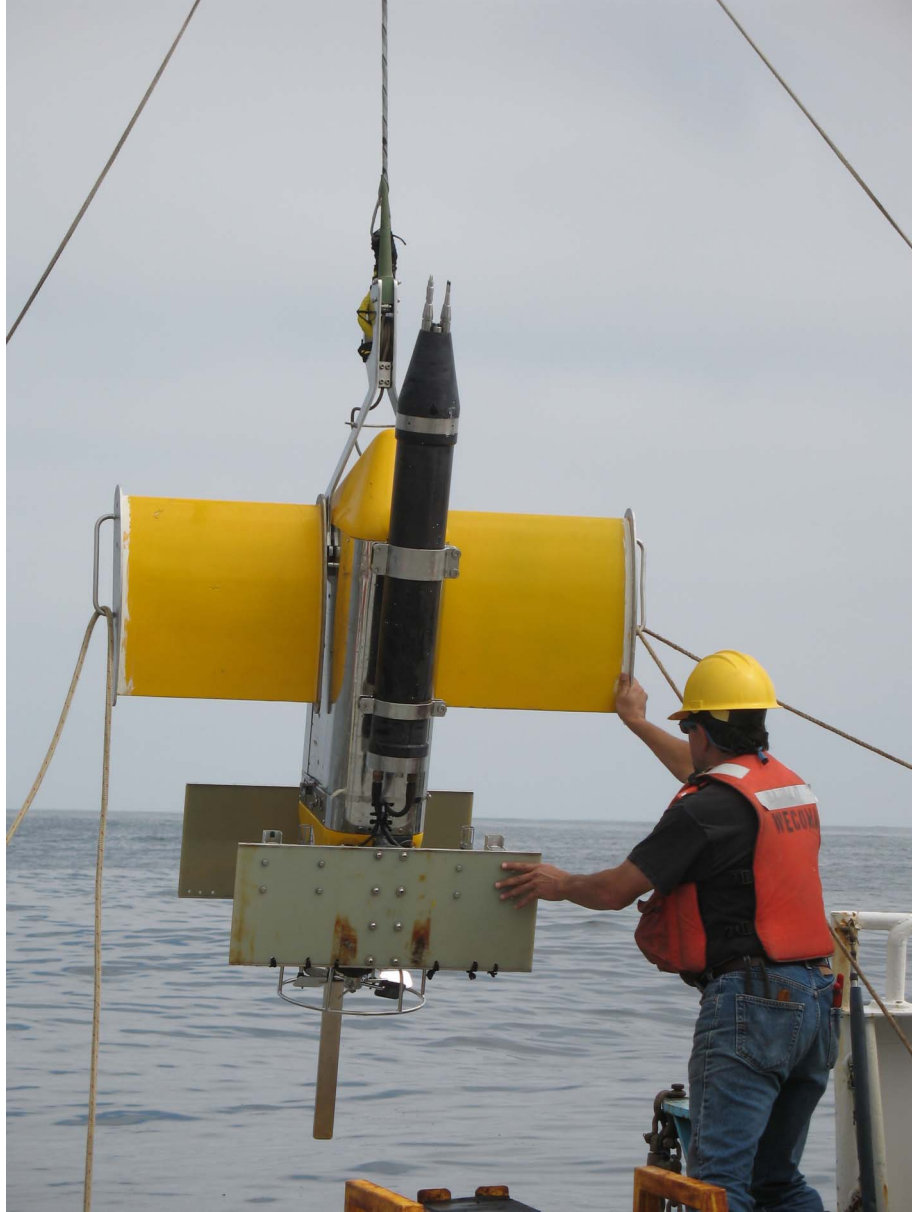
Figure 2. The black TMS is mounted below the yellow SeaSoar. The TMS has 2 micro-conductivity probes sampling at 2048 Hz and 2 fast thermistors sampling at 128 Hz. These probes are mounted forward of the SeaSoar body to obtain clean flow. Seabird T, C sensors are mounted on the grey horizontal stabilizers at the aft end of the SeaSoar.

Front survey. Our adaptive measurements were done in cooperation with Craig Lee and Eric D'Asaro (UW/APL), who deployed neutrally buoyant floats Lagrangian floats in the mixed layer on the east side of the front in southward flow and surveyed around them on the *Revelle* at a radius of <10 km with another towed vehicle, the Triaxus. Meanwhile the SeaSoar survey provided a roughly synoptic view of the mesoscale by covering 13 cross-front, ~70-km long sections twice in one week (Figures 3 and 4). We will collaborate with Lee, D'Asaro, and Ramsey Harcourt (UW/APL) on examining how submesoscale variability affects horizontal and vertical mixing processes in the boundary layer. The

SeaSoar and TMS data will be used to examine variability of the mixed layer base, subduction, and vertical mixing at the front.

Offshore line. A 400-km long offshore line was covered twice to examine the decay of submesoscale eddies and fronts away from the coast. A statistical approach will be used; we will calculate temperature gradient horizontal wavenumber spectra and vorticity probability distribution functions. These observations will compared with similar statistical descriptions from Xavier Capet and Jim McWilliams' high-resolution (750 m in the horizontal) regional model.
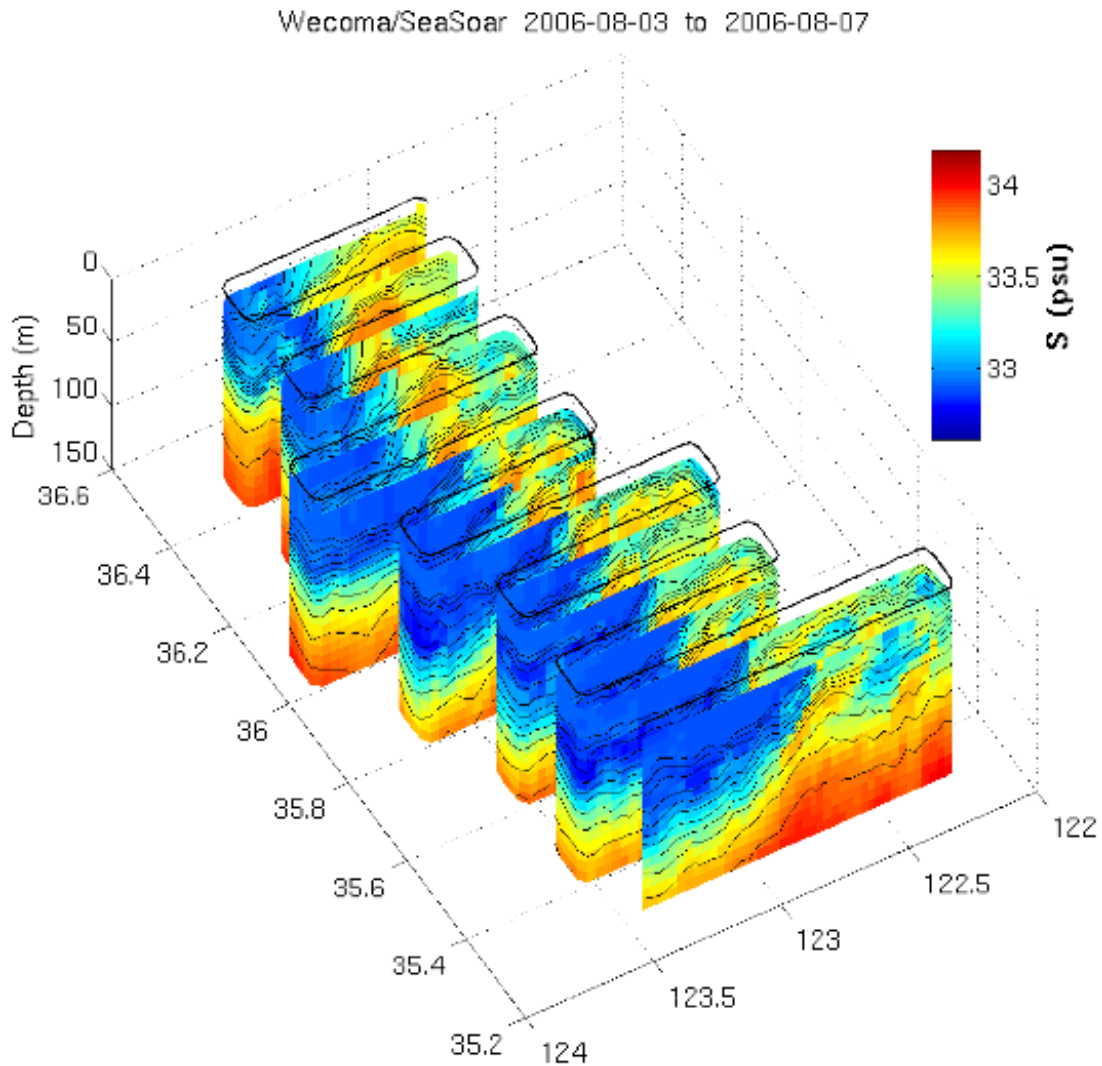

Figure 3. A 3D view of the second survey of the offshore front is shown. Salinity (S) is in colour and contours are isopycnals at 0.2 kg m^-3 intervals. The radiator pattern of the survey was centered on the front and crossed it thirteen times. The west side of front is warm and fresh, while the east side is cold and salty upwelled water. Isopycnals show water from the east side of the front is subducted below the water on the west side. Data are shown from 0-150 m only.

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Internal tide survey. The internal tide survey repeatedly surveyed three lines extending north of Sur Platform and across Monterey Canyon to a submarine fan, all of which are believed to generate internal tides [Lien and Gregg, 2001; Petruncio et al., 1998; Kunze et al., 2002]. These lines were repeated ~20 times each and at different tidal phase. Significant mesoscale variability was expected in this region and therefore three adjacent lines were surveyed near R/P *FLIP*. Velocity variance can be used to identify tidal beams and by averaging over tidal phase, internal tide energy flux and mixing can be measured. This work was crried out in conjunction with XCP/XCTD surveys by Eric Kunze (UVic) and James Girton (UW/APL) and high resolution time series at *FLIP* by Jody Klymak (UVic) and Rob Pinkel (SIO). Our data will be compared with the models of Steven Jachec and Oliver Fringer (Stanford) and Xiaochun Wang and Yi Chao (JPL).
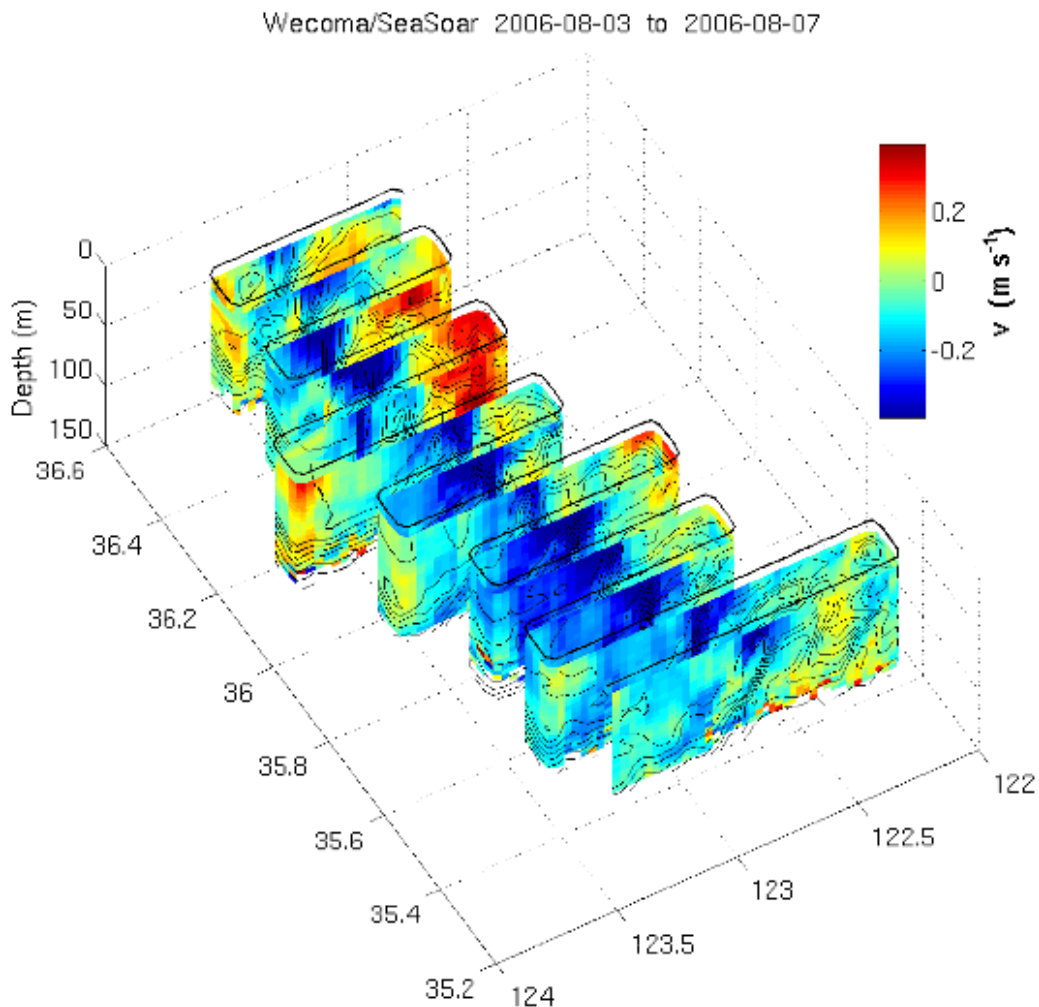

Figure 4. ***A 3D view of the second survey of the offshore front is shown. Northward velocity (v) is in colour and salinity is contoured at 0.1 psu intervals. Southward current is found on the west side of the front and northward current on the east side. Shear is found along the high density gradient at the front and also between water masses of differing salinity on the east side of the front. Data are shown from 0-100 m only from the 300 kHz ADCP, which has 4-m resolution, but limited range.***

Metrics for model-data comparison. In collaboration with other AESOP investigators, we produced a set of metrics, which would provide more stringent tests of models and insight into discrepancies than simply comparing temperature fields, for example. With our collaborators, we have acquired data to produce a coordinated comparison between observations and models of these metrics: vertical wavenumber spectra of shear and stratification; vorticity and horizontal gradients of temperature and salinity in the boundary layer; internal tide energy flux; and turbulent diffusivity and dissipation (Figure 5).
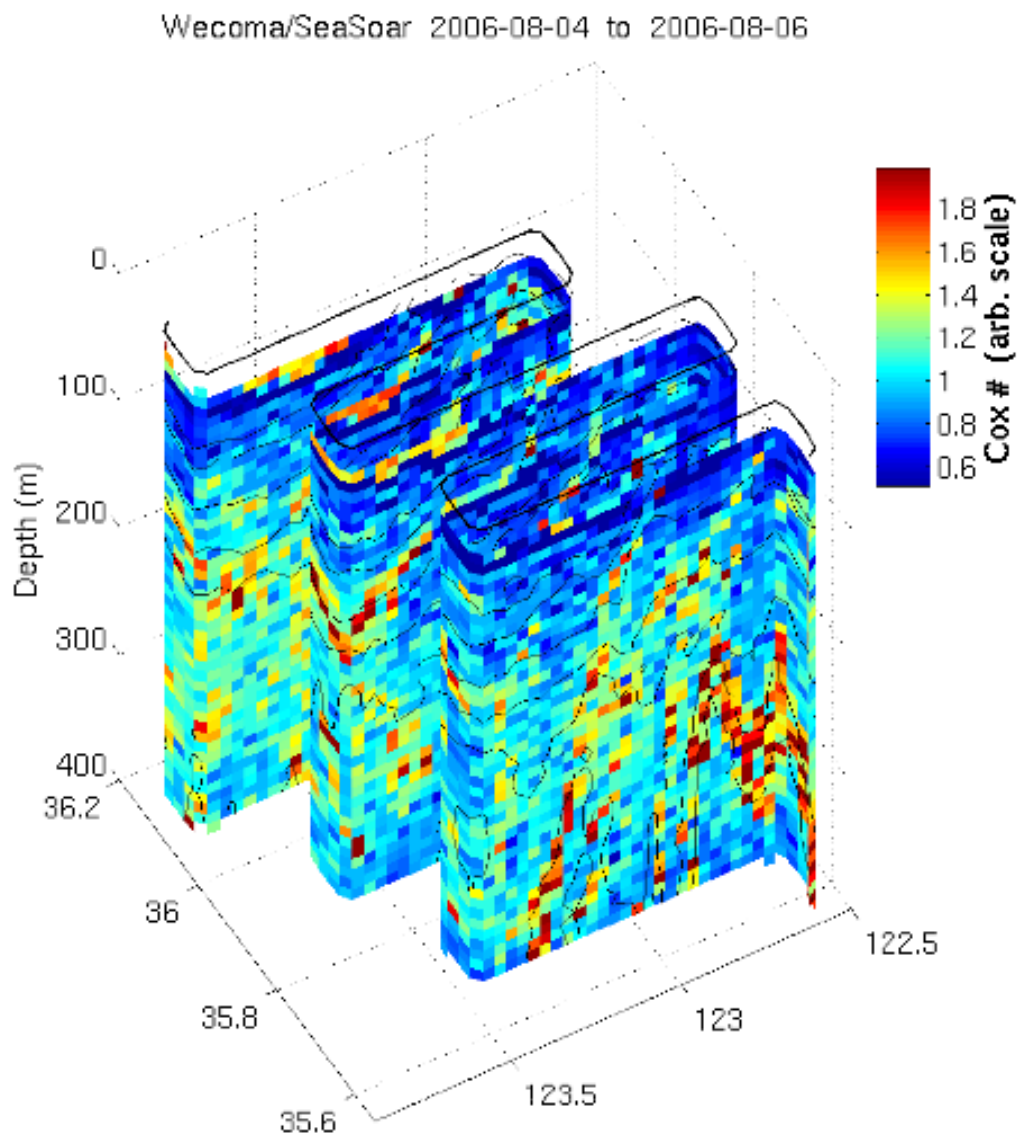

Figure 5. The Cox number approximation is plotted on a log scale and contours are salinity at 0.1 psu intervals. Mixing appears to be higher in shear zones between different water masses on the east side of the front and along a subducting, tilted isopycnal where current shear is high. Data are over a smaller lateral extent and a larger vertical extent than Figures 3-4.

WORK COMPLETED

The TMS was acquired from RGL Consulting and tested with SeaSoar during a test cruise from 25-27 October 2005 on R/V *Sproul*. Data transmission at 2000 Hz was achieved by coupling the high frequency AC signal from the TMS to the SeaSoar's wing control signal. Flight characteristics were normal with the TMS mounted below the SeaSoar. The microconductivity probes received clean flow and Batchelor wavenumber spectra were produced showing the inertial-convective and viscous-diffusive regimes of turbulence. Basic processing routines from RGL Consulting were modified to process the combined SeaSoar/TMS data. Carl Mattson and Rob Palomares (Shipboard Technical Support, SIO) prepared both instruments for operations on the cruises in 2005 and 2006.

From 29 July-28 August 2006 near Monterey Bay, we conducted a broad spatial survey of temperature, salinity, chlorophyll fluorescence, oxygen, beam transmission, currents, and turbulent vertical mixing. With a newer SeaCable we were able to sample at 2048 Hz with the TMS. The cruise on R/V *Wecoma* was divided into three segments: a mesoscale survey at a front between offshore water and upwelled water ~100 km offshore of Monterey Bay (Figures 3-5), a 400-km long offshore line to assess submesoscale decay away from the coast, and an internal tide survey near Monterey Canyon (Figures 6 and 7). In collaboration with other AESOP investigators, we have acquired data to produce a coordinated comparison of observations and models. Two graduate students, Sylvia Cole and Robert Todd (SIO), gained further practical experience working at sea and participated in analysis of the SeaSoar and ADCP data. Two interns, Mario Ruiz and Chris Vance (MATE Center, Monterey Peninsula Community College), participated in technical work, SeaSoar deployments and recoveries, and watchstanding on this cruise.

RESULTS

The TMS added to SeaSoar the valuable capability of measuring centimeter-scale temperature gradients and thus estimating turbulent mixing (Figures 5 and 7). We have just completed our cruise and only very preliminary results are available. The Cox number was approximated roughly: the variance of the despiked voltages from a microconductivity probe was calculated over 1-s intervals and then binned in 8-m by 3-km bins and divided by the similarly binned 8-m temperature gradient. The thermal eddy diffusivity is linearly related to Cox number [Dillon et al., 2003].

Enhanced mixing at the front appears to be found: 1) in a shear zone between different water masses and 2) along a subducting, tilted isopycnal where higher shear is also implied (Figures 3-5).

One or more internal tidal beams were identified by calculating velocity variance along ~60 cross-canyon sections derived from ~20 repeats of 3 lines separated by 2-4 km) (Figure 6). The beams appear to be generated at the Sur Platform, the canyon rims, and/or a submarine fan. Along these beams, it appears that the mixing measured by the TMS is elevated compared to background values (Figure 7). By averaging the many repeats of these lines, the signal-to-noise ratio was increased and the velocity structure of internal tidal beams and associated mixing was identified against the background of an energetic mesoscale.

IMPACT/APPLICATIONS

We will gain better understanding of submesoscale processes including mixed layer dynamics, transition layer variability, internal tides, and vertical mixing. Specifically, our data will be used to assess parameterizations with the following metrics: dissipation in the surface boundary layer (which includes the mixed layer and the transition layer) and shear layers; vorticity and horizontal gradients of temperature and salinity in the surface boundary layer; and internal tidal energy flux.

Our microstructure measurements from SeaSoar can be used to identify sites of enhanced mixing over a broad area at kilometer-scale resolution. Our measurements of stratification and shear can be used to estimate mixing with shear- and stratification-based parameterizations [Gregg, 1989; MacKinnon and Gregg, 2003] and the Thorpe scale [Martin and Rudnick, 2006]. All of these results can then be compared to parameterizations used in numerical models.
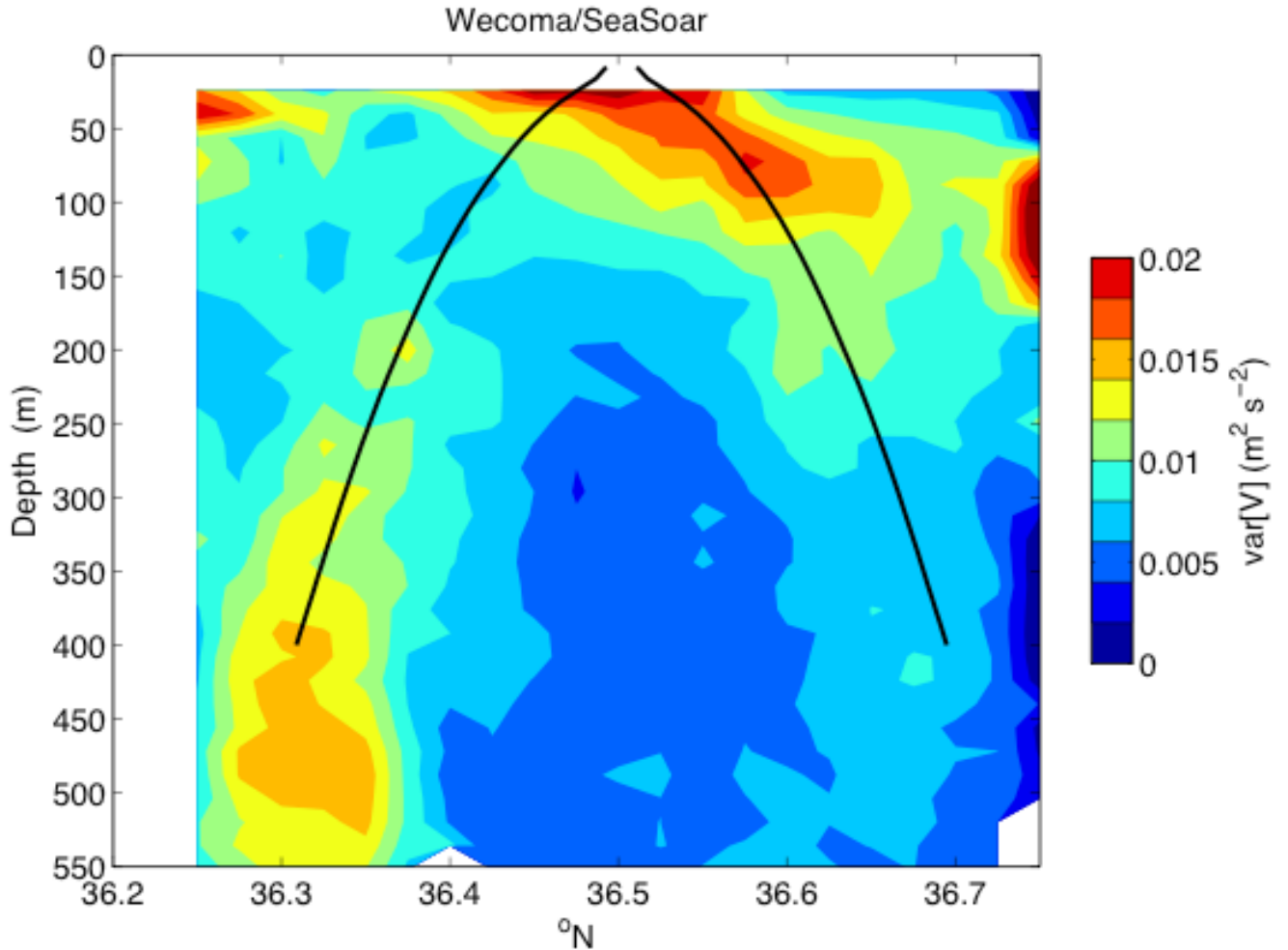

Figure 6. Northward velocity (v) variance in a meridional depth section from the narrowband 75 kHz Ocean Surveyor is calculated from ~60 repeat lines, which are obtained by combining twenty repeats of the three north-south lines across Monterey Canyon. Higher variance appears to be found along M_2 characteristics (black lines).
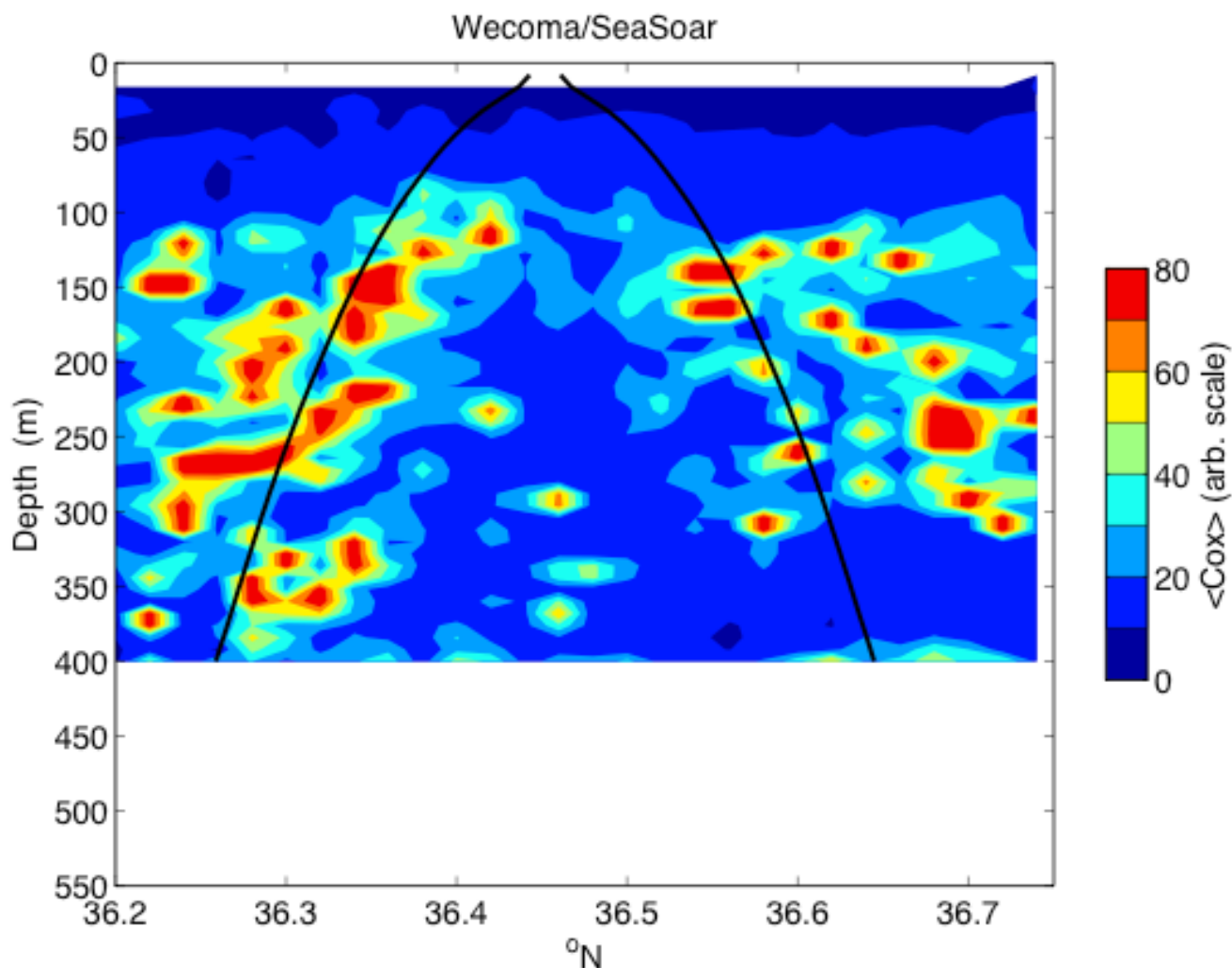
Figure 7. Mean Cox number in a meridional depth section is calculated from ~20 repeat lines, which are obtained by combining about six repeats of the three north-south lines across Monterey Canyon. Higher mean values appear to be found along M₂ characteristics (black lines).

RELATED PROJECTS

AESOP collaborations are noted above.

While at sea we provided daily updates of data including temperature, salinity, density, fluorescence, and currents to the Adaptive Sampling and Prediction (ASAP) experiment to assimilate in their regional models. Improvement in the ASAP model predictions was noted, when our upstream measurements were included. See http://aosn.mbari.org/coop/. Further collaboration is expected.

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